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Original Article

A Review of the Progress with Statistical Models of Passive Component Reliability

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ABSTRACT

During the past 25 years, in the context of probabilistic safety assessment, efforts have been directed towards establishment of comprehensive pipe failure event databases as a foundation for exploratory research to better understand how to effectively organize a piping reliability analysis task. The focused pipe failure database development efforts have progressed well with the development of piping reliability analysis frameworks that utilize the full body of service experience data, fracture mechanics analysis insights, expert elicitation results that are rolled into an integrated and risk-informed approach to the estimation of piping reliability parameters with full recognition of the embedded uncertainties. The discussion in this paper builds on a major collection of operating experience data (more than 11,000 pipe failure records) and the associated lessons learned from data analysis and data applications spanning three decades. The piping reliability analysis lessons learned have been obtained from the derivation of pipe leak and rupture frequencies for corrosion resistant piping in a raw water environment, loss-of-coolant-accident frequencies given degradation mitigation, high-energy pipe break analysis, moderate-energy pipe break analysis, and numerous plant-specific applications of a statistical piping reliability model framework. Conclusions are presented regarding the feasibility of determining and incorporating aging effects into probabilistic safety assessment models.

1. Introduction

Nuclear power plant piping systems are robustly designed and carefully fabricated. However, even a well-designed piping system can develop through-wall leaks or ruptures. Piping reliability analysis has been a topic of discussion and concern within the nuclear safety community for a long time [1]. In part, this concern has been related to the capabilities and limitations of available methods and techniques, as well as with the requirements for how to best perform “pedigreed” quantitative analysis in support of probabilistic safety assessment (PSA) applications. The introduction of risk-informed in-service inspection (RI-ISI) [2], risk-informed resolution of generic safety issue (GSI)-191 [3], and the evolving

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internal flooding PSA methodology [4] are but three examples of how nuclear industry initiatives have contributed to the current set of pipe failure databases and associated analysis tools and techniques. Analytical insights from a broad spectrum of piping reliability analysis case studies performed over a 2-decade period have been translated into a guideline for how to structure a robust piping reliability analysis task in support of practical, PSA-oriented applications.

The team of analysts responsible for the seminal Reactor Safety Study (WASH-1400) [5] performed a limited evaluation of nuclear power plant piping reliability based on service experience from the then approximately 150 U.S. commercial nuclear reactor operating years [6]. This evaluation was aimed at estimating loss-of-coolant-accident (LOCA) frequencies for input to the two PSA models (Peach Bottom Unit 2 PSA and Surry Unit 1 PSA) that constituted the Reactor Safety Study. After the publication of WASH-1400 in 1975, many other research and development projects have explored the roles of structural reliability models and statistical evaluation models in providing acceptable input to PSA. Furthermore, during the past 20 years' efforts have been directed towards the establishment of comprehensive pipe failure event databases as a foundation for exploratory research to better understand the capabilities of today's piping reliability analysis frameworks.

Against a historical overview of past efforts, this paper addresses the question how to best utilize service experience data for quantitative piping reliability analysis. Significant progress has been made to develop pipe failure databases, as well as analysis tools to explore and analyze the body of service experience with piping from today's well over 15,000 commercial reactor operating years and 11,000+ records on pipe degradation and failure events. Insights from 25 years of pipe failure database applications and method development are utilized to reach some conclusions about the capability of statistical analysis approaches to piping reliability analysis. Also addressed are guidelines and good practices for how to optimize the utilization of service experience data when structuring piping reliability analysis strategies.

The ability of an event database to support practical applications is closely linked to its completeness and comprehensiveness. Equally important is the knowledge and experience of an analysts in interpreting and applying a database given typical project constraints. Achievement of database "completeness" and "comprehensiveness" is motivated by an in-depth understanding of the application requirements. These requirements are linked to three general types of applications: (1) high-level; (2) risk-informed; and (3) advanced database applications. Here the term "risk-informed" implies an application that is performed using the best available and most current information concerning piping degradation mechanisms and their mitigation, and in a context of the current probabilistic safety assessment practice.

Data specialization is an intrinsic aspect of all PSA oriented applications. This encompasses several specific analysis tasks such as the review and assessment of the applicability of industry-wide service experience data to a plant-specific piping design (e.g., material, dimension, piping layout, and operating environment), development of *a priori* failure rate distribution parameters reflective of unique sets of piping reliability attributes and influence factors, and Bayesian update of apriori distributions. The update may encompass consideration of different "what-if" scenarios such effect of different degradation mechanism (DM) mitigation strategies or impact of a corrosion resistant material as opposed to carbon steel.

2. Historical review

The WASH-1400 study included an evaluation of piping reliability to derive "order-of-magnitude" LOCA frequencies and pipe failure rates. Different, nuclear, and non-nuclear sources of service experience data and pipe failure rate data were utilized for the purpose of extrapolating pipe failure rates for input to the PSA models of the WASH-1400 study.

With funding from the US Nuclear Regulatory Commission Office of Research, the Idaho National Laboratory has performed studies to update the LOCA frequencies of WASH-1400. The report NUREG/CR-4407 [7] accounted for the accumulated US service experience through December 1984, and NUREG/CR-5750 [8] expanded the evaluation to account for service experience through end of 1997. The nuclear industry through the Electric Power Research Institute (EPRI) has also sponsored research and development to develop databases and associated methods and techniques for piping reliability analysis [9–11]. During 2003–2006, the Nuclear Regulatory Commission established an "Expert Panel on Loss-of-coolant Accident Frequencies" [12] to develop LOCA frequencies for boiling water reactor (BWR) and pressurized water reactor plants. An expert elicitation process was utilized to consolidate service experience data and insights from probabilistic fracture mechanics (PFM) with knowledge of plant design, operation, and material performance. LOCA frequencies were developed for three distinct time periods: (1) present-day estimates; (2) end-of-plant life (i.e., at time $T = 40$ years); and (3) at $T = 60$ years estimates to reflect state at the end of a first license renewal cycle.

In the late 1980s, the American Society of Mechanical Engineers (ASME) recognized the need for risk-informed methods in the formulation of codes and standards, and guides by organizing a research task force on RI-ISI. From this work, ASME was able to demonstrate that risk-informed methods offered the potential to technically enhance the existing ISI programs. The current RI-ISI methodology includes extensive considerations of piping reliability. The methodology, process, and rationale used to determine the likelihood of pipe failure is required to be scrutable and available for independent review. The RI-ISI initiatives refocused the investigations into the application of service experience data to derive insights about pipe failure potential and pipe failure probability. An intrinsic technical aspect of these RI-ISI initiatives is the role of new piping service experience and its potential influence on an existing RI-ISI program plan.

In a series of reports by the Swedish Radiation Safety Authority [13–15], the evolution of statistical models of piping reliability is summarized; from the mid-1960s to the mid-

1990s. During this period, the attempts to model piping reliability on the basis of service experience data were hampered by a scarcity of well-structured information sources on observed pipe failures in commercial nuclear power plants. During the following 2 decades, significant progress has been made both with respect to the development of comprehensive pipe failure databases, and holistic data analysis frameworks and quantitative assessment of the full range of piping reliability parameters [16].

3. Piping reliability analysis considerations

Using terminology from the ASME/American Nuclear Society (ANS) PSA Standard, "Capability Categories" are assigned to the different elements of a PSA to determine its quality and its ability to support a certain application. For risk significant accident scenarios, achievement of Capability Category II or III is expected. In general, this is, in part, achieved through application of plant-specific operating experience data; either selectively or exclusively, depending on the specific application requirements. In other words "data specialization" is an important part of PSA model maintenance and application. Data specialization involves updating generic, industry-wide data parameters with plant-specific data. Typically, the data updating is accomplished using a Bayesian parameter estimation approach in which well qualified generic data is represented by a prior distribution. For piping reliability, data specialization includes tasks such as:

- Update of existing piping reliability parameter estimates by using new operating experience data. We refer to this as "routine" or ordinary data specialization in which a new set of operating experience data is incorporated into an existing analysis.
- Modifying generic piping reliability parameter estimates to account for impact on the structural reliability by changes to an inspection program, or DM mitigation through an application of a full structural weld overlay or mechanical stress improvement process, or the replacement of an existing piping system by using a DM-resistant material.
- Derivation of DM-centered pipe failure rates and rupture frequencies. Included in this task is development of conditional rupture probability (CRP) models that are conditional on the presence of a specific active or assumed inactive degradation mechanism.
- Derivation of piping reliability parameters for new reactor designs on the basis of existing industry-wide operating experience data to a new piping design for which there is no prior operating experience. This type of data specialization involves a very structure application of the full knowledgebase that is associated with the lessons learned from the Generation I through III commercial nuclear power reactor operating experience.
- For some PSA applications pipe rupture frequencies have been developed for different through-wall flow rate categories. For example, "spray events" ($\leq$5 kg/s), "general flooding" (between 5 kg/s and 100 kg/s), and "major flooding" (>100 kg/s). To remove conservatism a refined treatment of flow rate ranges to parse the pipe rupture frequency for flow rate ranges of varying sizes may be warranted.

The quality of a data specialization task is a function of the analyst's knowledge and experience and how a parameter estimation task is structured to adequately address a specific application requirement. Guidelines and best practices for piping reliability analysis have been developed [17] that address:

- Knowledge Base: a fundamental basis for a qualified piping reliability analysis rests on a deep understanding of how, the typically robust metallic piping systems degrade and fail or sustain damage due to different off-normal operating environments. Also of importance is a deep understanding of piping system design principles, including the different piping construction/fabrication practices.
- Operating Experience Data: under what conditions can operating experience data support quantitative piping reliability analysis? The completeness and comprehensiveness of a database are essential characteristics for a database to support the derivation of "robust" reliability parameter estimates.
- Qualitative Analysis Requirements: query functions are defined to extract event population and exposure term data from a comprehensive relational database. Oftentimes, a query definition must address a complex set of reliability attributes and influence factors. The characterization of aleatory and epistemic uncertainties depends on the intrinsic qualities of a query definition.
- Quantitative Analysis Requirements: pipe failure rate calculation is based on event populations that reflect different piping designs. Therefore, an established practice is to apply a Monte Carlo posterior weighting technique to synthesize the variability in weld counts and DM susceptibility. Pipe rupture frequencies are calculated for well-defined break sizes and resulting through-wall flow rates. CRP models are required for a predefined set of break size ranges.
- Special Considerations: certain follow-up (or sensitivity) studies may have to be performed once a base case set of reliability parameters have been obtained.

3.1. *Piping reliability analysis knowledgebase*

Metallic piping degrades and fails due to synergistic effects of off-normal operating and environmental conditions, and unusual or extreme loading conditions. The triplet material/environment/loading represents the conjoint requirements for pipe degradation. Making, sometimes, subtle changes to any of the physical parameters (e.g., pH, corrosion potential, H_2 content, temperature, flow rate, carbon content, postweld heat treatment) that are embedded in this triplet can have a profound effect on the pipe degradation propensity. Therefore, a piping reliability analysis task must reflect a basic understanding of the roles of, e.g., metallurgy, water chemistry, and pipe stresses in the achievement of high structural reliability. An example of data specialization is to make an estimate of the impact on piping reliability by using different material grades. Another example is to quantify the improvement in reliability by applying a stress relief process on a certain weld location.

The currently available operating experience consists of two general types of pipe failures: (1) failures that are due to environmental degradation; and (2) event- or stress-driven failures (often referred to failures that are attributed to damage mechanisms). The former is characterized by an incubation time for a flaw to develop followed by propagation in the through-wall direction. Flaw propagation occurs due to some driving force, e.g., weld residual stresses. These failures are time-dependent and may develop over a long-time period (e.g., several decades). The latter are due to upstream or downstream equipment failures or significant hydraulic transients. Under certain conditions, an event-based condition acts as an initiation site for subsequent environmental degradation.

Certain combinations of DM-susceptibility/damage susceptibility, material, and operating environments have produced major structural failures (e.g., double-ended guillotine break). By contrast, carefully applied material selection principles have resulted in robust piping systems with no evidence of through-wall defects. Pipe degradation and failure is avoidable. A selected analysis strategy is needed to reflect a deep understanding of the fundamental principles of pipe degradation and failure, as well as acknowledgement of piping design principles, codes, and standards and in-service inspection practices and requirements. However, there is no single-fit-for-all analysis strategy. Applications that concern piping subjected to aggressive degradation mechanisms such as flow-accelerated corrosion should be evaluated using analysis techniques different from those employed to address situations where degradation is highly localized and progresses over a long time.

3.2. *Piping operating experience data*

Since the publication of NUREG/CR-6157 [18], substantial progress has been made relative to the development of dedicated pipe failure databases [19]. Since an event database includes information on historical events, the completeness of the event population in the database always is an important factor in determining its “fitness-for-use.” This needs to be placed in a perspective of the present-day knowledge about incubation times of pipe flaws: short versus long.

Five types of metrics are considered in quantitative piping reliability analysis in PSA: (1) failure rate; (2) conditional failure probability; (3) inspection effectiveness; (4) DM mitigation effectiveness; and (5) aging factors. For a pipe failure event database to support failure rate estimation it must include extensive piping system design information that yield information on the total piping component population that has produced the failure observations. In other words, the database must include event population data as well as exposure term data. Relative measures of piping reliability such as conditional failure probabilities can be generated by querying an event database without access to exposure term data, however. The statistical robustness of such relative measures is strongly correlated with the completeness of the event population.

Completeness and comprehensiveness of an operating experience database is ensured through a sustained and systematic maintenance and update process. Completeness is an indication of whether or not all the data necessary to meet current and future analysis demands are available in the database. The comprehensiveness of a service experience database is concerned with how well its structure and content correctly capture piping reliability attributes and influence factors. A clear basis should be included for the identification of events as failures.

Based on practical experience, the inherent latency in structured data collection efforts is on the order of 5 years. This means that *circa* 5 years could elapse before achievement of high confidence in data completeness. In other words, in around 2020 the data mining for the previous 10 years (2005–2015) would be expected to approach “saturation” (as in high confidence in completeness of a database). Could “cliff-edge effects” (e.g., a small change in input parameter value resulting in large results variation) affect an analysis due to database infrastructure factors? It depends on the maturity of inspection programs and our state-of-knowledge concerning certain degradation mechanisms. Considerations about the use of up-to-date failure data is intrinsically assumed to be factored into an analysis task.

The design of and infrastructure associated with a service experience database should be commensurate with application demands and evolving application requirements. In PSA, the completeness of a relevant event population should be validated, either independently or assured through a sustained and carefully documented maintenance effort. To achieve the objectives defined for a database, a data classification format should be established and documented in a Coding Guideline. Such a guideline is built on recognized pipe failure data analysis practices and routines that acknowledge the unique aspects of piping reliability in commercial nuclear power plant operating environments. For an event to be considered for inclusion in the database it must undergo an initial screening for eligibility. An objective of this initial screening is to go beyond abstracts of event reports to ensure that only pipe degradation and failures according to a certain work scope definition are included in the database. As stated, the knowledge and experience of the analyst is a key to performing well-qualified piping reliability analysis.

Data quality is affected from the moment the operating experience data is recorded at a nuclear power plant, interpreted, and finally entered into a database system. The operating experience data is recorded in different types of information systems ranging from work order systems, via in-service inspection databases, and outage summary reports, to licensee event reports. Consequently the details of degraded condition or failure tend to be documented at various levels of technical detail in these different information systems.

Building a database event record containing the full event history often entails extracting information from multiple sources. The term "data quality" is an attribute of the processes that have been implemented to ensure that any given database record (including all of its constituent elements, or database fields) can be traced to the source information. The term also encompasses "fitness-for-use", that is, the database records should contain sufficient technical detail to support database applications.

3.3. *Qualitative data analysis*

Correlating an event population with the relevant plant and component populations that produced these failure events enables the estimation of reliability parameters for input to a calculation case. The information contained in a database must be processed according to specific guidelines and rules to support reliability parameter estimation. A first step-in data processing involves querying the event database by applying data filters that address the conjoint requirements for pipe degradation and failure. These data filters are an integral part of a database structure. Specifically, the data filters relate to unique piping reliability attributes and influence factors with respect to piping system design characteristics, design and construction practice, ISI, and operating environment. A qualitative analysis of service experience data is concerned with establishing the unique sets of calculation cases that are needed to accomplish the overall analysis objectives and the corresponding event populations and exposure terms.

Most, if not all database applications are concerned with evaluations of event populations as a function of calendar time, operating time, or component age at time of failure. The technical scope of the evaluations includes determination of trends and patterns and data homogeneity, and assessment of various statistical parameters of piping reliability. Therefore, an intrinsic aspect of practical database applications is the completeness and quality of an event database. Do the results of an application correctly reflect the effectiveness of in-service inspection, aging management, and/or water chemistry programs?

Before commencing with a statistical parameter estimation task, it is essential to develop a thorough understanding of the range of influence factors that act on metallic piping components. Database "exploration" (or data reduction) should be an integral part of all qualitative analysis steps to

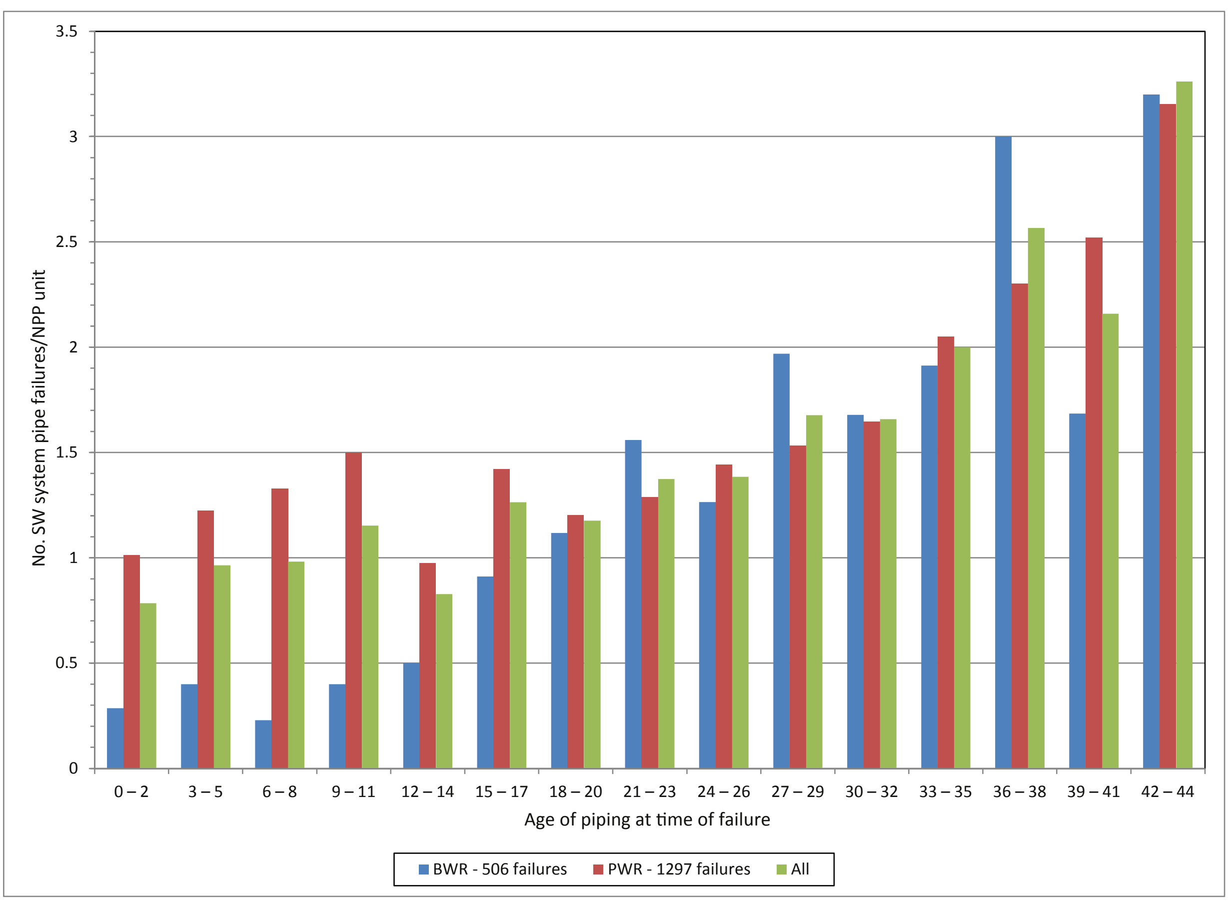

Fig. 1 – US safety-related service water (SW) pipe failure data. BWR, boiling water reactor; NPP, nuclear power plant; PWR, pressurized water reactors.

ensure that the defined evaluation boundary is associated with the most relevant event population data and exposure term data. It entails the identification of unique event subpopulations, time trends/temporal changes and dependencies. Displayed in Figs. 1 and 2 are high-level summaries of the pipe failure experience involving corrosion failures and flow-assisted degradation, respectively.

In Fig. 1 the US-specific service water (SW) system pipe failure data is organized as a function of piping component age at time of failure. Different types of corrosion failures are the predominant cause of through-wall leaks. While carbon steel remains a predominant material, different types of stainless steel are also used to improve corrosion resistance. The SW pipe failure data is averaged across the entire US plant population. Hence, the plant-to-plant variability of the SW piping performance is obscured. Some insights into the development of plant-specific SW pipe failure rates are addressed in Section 5.

Fig. 2 summarizes pipe failure experience by four types of flow-assisted degradation mechanisms: (1) erosion corrosion; (2) erosion cavitation; (3) flow-accelerated corrosion (FAC); and (4) liquid droplet impingement erosion. Carbon steel material is potentially susceptible to the erosion corrosion and FAC mechanisms, whereas carbon steel, low-alloy-steel, and stainless steel materials are potentially susceptible to the erosion cavitation and liquid droplet impingement erosion mechanisms. The very significant differences in the failure trends also impact the analysis strategies for pipe failure rate and rupture frequency estimation.

3.4. *Quantitative data analysis*

The technical approach to estimating pipe failure rate rates and rupture frequencies is based on the model expressed by Eqs. (1) and (2) for estimating the frequency of a pipe break of a given magnitude. Typically, the magnitude is expressed by an equivalent break size and corresponding through-wall flow rate. The parameter x is treated as a discrete variable representing different equivalent break-size ranges.

$$F(IE_x) = \sum_i m_i \rho_{ix} \quad (1)$$

$$\rho_{ix} = \sum_k \lambda_{ik} P(R_x|F_{ik}) I_{ik} \quad (2)$$

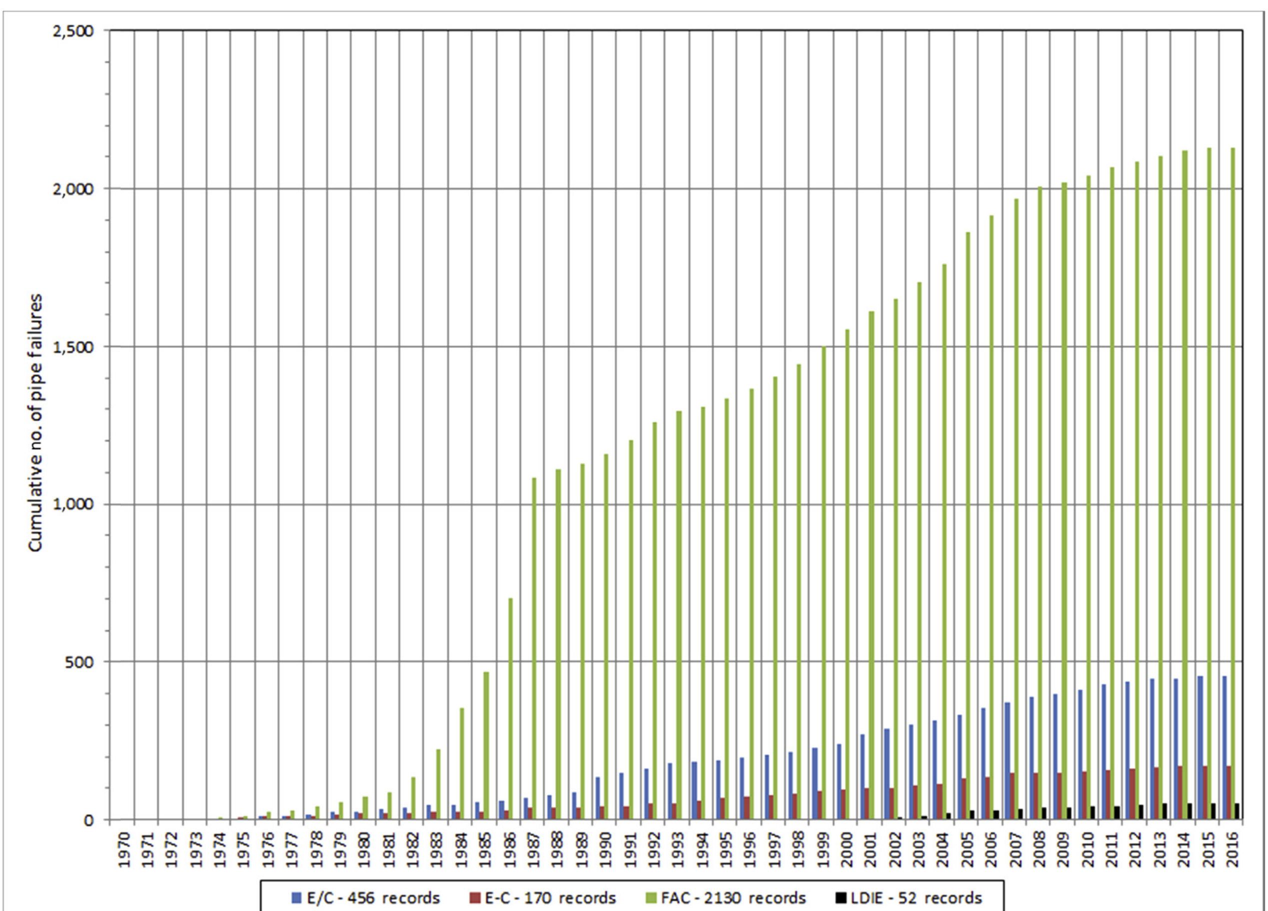

Fig. 2 – Data on pipe failures attributed to flow-assisted degradation. E/C, erosion-corrosion; E-C, erosion cavitation; FAC, flow-accelerated corrosion; LDIE, liquid droplet impingement erosion.

Where

$F(IE_x) =$	Frequency of pipe break of size x, per reactor operating year, subject to epistemic uncertainty calculated via Monte Carlo simulation.
m_i	Number of pipe locations of type i; each type determined by pipe size, weld type, applicable damage or degradation mechanisms, and inspection status (leak test and nondestructive examination).
ρ_{ix}	Frequency of rupture of component type i with break size x, subject to epistemic uncertainty calculated via Monte Carlo simulation or lognormal formulas.
λ_{ik}	Failure rate per "location year" for pipe component type i due to failure mechanism k, subject to epistemic uncertainty determined by Bayes methodology.
$P(R_x\|F_{ik}) =$	CRP of size x given failure of pipe component type i due to damage or degradation mechanism k, subject to epistemic uncertainty. This parameter may be determined on the basis of expert elicitation or service experience insights.
I_{ik}	Integrity management factor for weld type i and failure mechanism k, subject to epistemic uncertainty determined by Monte Carlo simulation and Markov model.

Point estimates of the failure rate λ_{ik} of piping component of type i and degradation mechanism k is obtained through:

$$\lambda_{ik} = \frac{n_{ik}}{\tau_{ik}} = \frac{n_{ik}}{f_{ik} N_i T_i} \tag{3}$$

Where

$n_{ik} =$	Number of failures in pipe component (i.e., weld) type i due to failure mechanism k; very little epistemic uncertainty. The component boundary used in defining exposure terms is a function of DM.
$\tau_{ik} =$	Component exposure population for welds of type i susceptible to failure mechanism k, subject to epistemic uncertainty determined by expert opinion.
$f_{ik} =$	Estimate of the fraction of the component exposure population for weld type i that is susceptible to failure mechanism k, subject to epistemic uncertainty, estimated from results of RI-ISI for population of plants and expert opinion.
$N_i =$	Estimate of the average number of pipe welds of type i per reactor in the reactor years exposure for the data query used to determine n_{ik}, subject to epistemic uncertainty, estimated from results of RI-ISI for population of plants and expert knowledge of damage mechanisms.
$T_i =$	Total exposure in reactor-years for the data collection for component type i; little or no uncertainty.

Applying the above seemingly simple relationships invariably result in significant analysis efforts, however. First, the failure event population(s) must fully match a selected evaluation boundary; i.e., piping system of certain material and in a specific operating environment. Oftentimes, the exposure term definition involves extensive reviews of isometric drawing information to correctly address plant-to-plant piping system design variability, which is essential in correctly matching event populations and exposure terms.

For a Bayes' estimate, *a prior* distribution for the failure rate is updated using n_{ik} and τ_{ik} with a Poisson likelihood function. The formulation of Eq. (3) enables the quantification of conditional failure rates, given the known susceptibility to the given damage or degradation mechanism. When the parameter f_{ik} is applied, the units of the failure rate are failures per welds susceptible to the damage or degradation mechanism. This formulation of the failure rate estimate is done because the susceptible damage or degradation mechanisms typically are known from the results of a previously performed degradation mechanism analyses. If the parameter f_{ik} is set to 1.0, the failure rates become unconditional failure rates, i.e., independent of any knowledge about the susceptibility of damage or degradation mechanism, or alternatively that 100% of the components in the population exposure estimate are known to be susceptible to a certain damage or degradation mechanism.

The likelihood of a pipe flaw propagating to a significant structural failure is expressed by the conditional failure probability $P(R_x|F_{ik})$ where F_{ik} represents degraded condition. This term is of significance whenever no operating experience data exists for very significant structural failures. When it is not feasible to do a direct statistical estimation of the conditional probability the assessment can be based on probabilistic fracture mechanics (PFM), expert judgment, and/or operating experience data insights, and/or expert judgment. Different PFM algorithms have been developed, but with a focus on fatigue growth and stress corrosion cracking [20].

There remain issues of dispute with respect to reconciliation of results obtained through statistical estimation versus the physical models of PFM, however. Results from studies to benchmark PFM calculations against field experience have shown PFM computer codes to over-predict pipe failure rates by more than an order magnitude relative to statistical estimates of field experience data. In general, the results obtained with PFM computer codes are quite sensitive to assumptions about weld residual stresses, crack growth rates, and correlations of crack initiation times and growth rates. Also, PFM calculations are invariably done for very specific geometries that may or may not apply to a broader set of evaluation boundaries under consideration in PSA.

4. A proposed PFM/statistical model interface

In some early applications, a simple Beta distribution formulation was used to estimate the conditional probability [21]. The main issue with assuming a prior Beta distribution is the estimation of its parameters. Several "constrained" approaches have been proposed. Methods to determine the parameters of the prior Beta distribution include: the method of moments, the program evaluation and review technique (PERT) approach, or the Pearson–Tukey approach [22]. In the absence of data, noninformative priors appear to be a straightforward solution. However, there is often a good knowledge on one constraint, such as the mean probability. The use of a constrained noninformative prior seems to be especially relevant to situations where limited failure data are available to assess the probability that a structural failure occurs, given a degraded condition. In the Pearson–Tukey approach a subject matter expert (SME) is asked to provide the fifth, 50th, and 95th percentiles and these statistical estimates are used to determine the parameters of a Beta prior distribution. Illustrated in Fig. 3 are different CRP versus equivalent break size correlations. These correlations are specific to certain degradation mechanism and material combinations.

As an example, in Fig. 3, the CRP correlations for FAC in single-phase and two-phase flow systems have been derived directly from service experience data. The CRP correlation for intergranular stress corrosion cracking (IGSCC) in BWR systems has been derived using the expert elicitation results of NUREG-1829 and the Pearson–Tukey approach. The CRP correlations for the other degradation mechanisms have been derived on the basis of material property data, laboratory test data, service experience data, and expert judgment.

5. Special considerations and case studies

A typical piping reliability analysis develops pipe rupture frequencies in terms of cumulative frequencies as a function of break size as well as through-wall flow rate. Both tabular and graphical formats are used to present the results. Additional data specialization may be required to support analysis of pipe break scenarios for which the consequences are substantially different if the time to perform an operator action (e.g., break isolation) is highly flow-rate sensitive. This could be the case in the analysis of pipe failure induced internal flood scenarios.

The applications tend to be computationally intense. In order to derive input to a PSA model, several calculation cases must be defined to cover the appropriate range of degradation mechanisms and consequences of a pipe failure. A calculation case is defined by a unique set of pipe rupture frequency versus consequence of a certain, well-defined magnitude usually characterized by either the size of a pressure boundary breach and/or through-wall flow rate. In support of a Significance Determination Process [23], a total of 24 calculation cases were defined. A failure rate and rupture frequency distribution had to be developed for each case, and, hence a total of 48 parameter distributions were generated. In developing a location-specific LOCA frequency model [3], a total of 45 unique analysis cases were defined and a total of 462 parameter distributions were generated.

A carefully crafted analysis tool is needed to manage the calculation of piping reliability parameter distributions. The case studies referred to in this paper are based on an open Microsoft Excel spreadsheet format with suitable add-in programs for uncertainty propagation and Bayesian update operations. With the advancements in analysis methods and

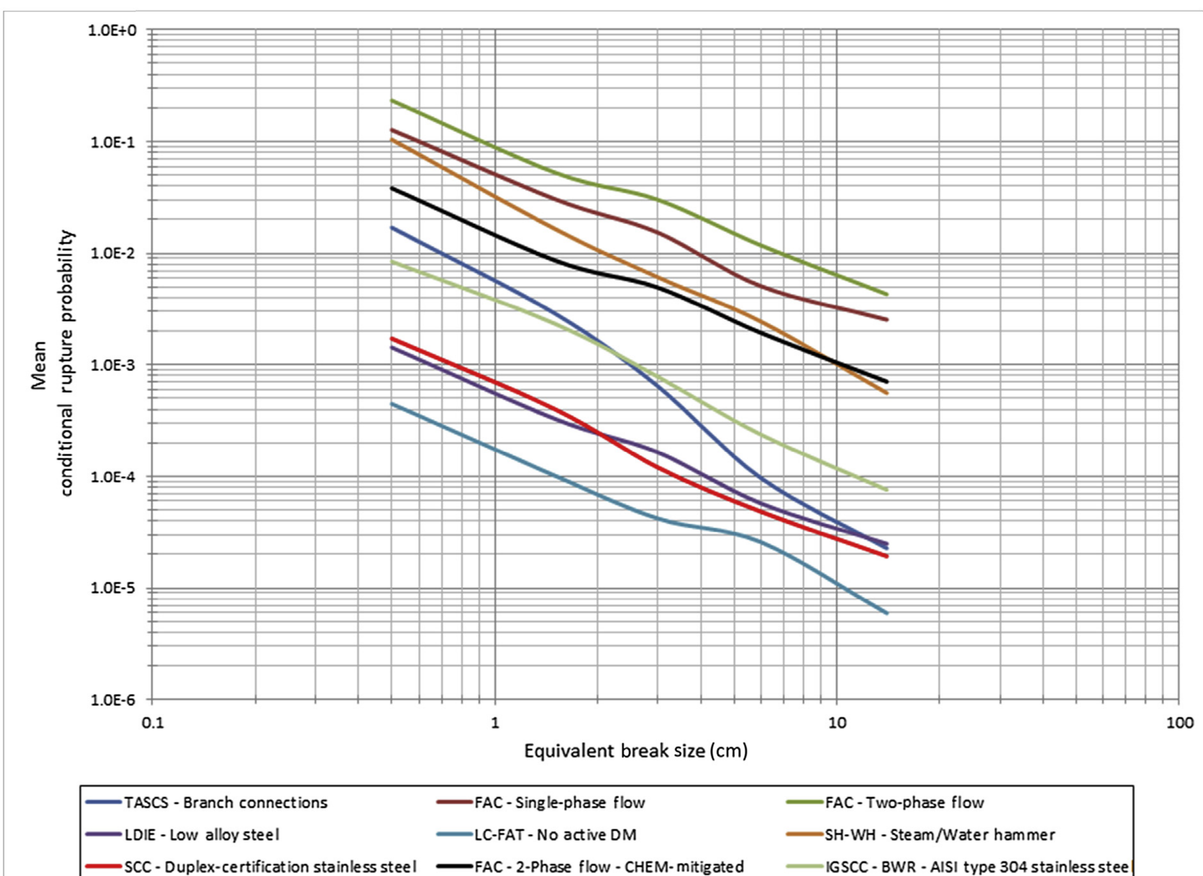

Fig. 3 – Empirical and theoretical conditional rupture probability correlations. FAC, flow-accelerated corrosion; LC-FAT, low-cycle fatigue; LDIE, liquid droplet impingement erosion; SCC, XXX; SH-WH, XXX; TASCS, XXXX.

techniques follow new challenges in how to review and validate parameter distributions and the propagation of uncertainties. The entire process, from definition of calculation cases, definition of pipe failure database queries, definition of prior distributions, and performing calculations must be traceable and transparent to ensure efficient review processes.

5.1. *Data specialization: a case study*

Most operating nuclear power plants employ carbon steel piping in the plant service water systems. The generic failure rates for service water piping in EPRI Report 3002000079 [11] are based on service experience from these carbon steel-based systems. Some nuclear power plant owners have been introducing corrosion resistant materials (e.g., high-performance or super-austenitic stainless steels) in upgrades to the plant SW systems intended to minimize the types of corrosion that has been experienced in the service data. The question to address is how much more reliable are these new corrosion resistant materials in preventing pipe leaks and ruptures.

As there is insufficient operating experience to estimate corrosion resistant pipe failure rates directly from the service data, the approach used in this study was to analyze the generic data from pressurized water reactor SW systems and screen the pipe failures according the degradation mechanisms that are expected to be either prevented or mitigated by the corrosion resistant materials. As a result of the greater reliance on expert judgment, the uncertainties in the failure rate estimates are significantly greater than those provided in EPRI Report 3002000079. Three different hypotheses about the corrosion resistance were formulated with probability weight assigned each hypothesis to produce a mixture distribution probability matrix. The calculated failure rate reduction factors ranged from 16% to 46%. The uncertainty in the reduction factors was assessed using a constrained noninformative distribution. Finally, the results of the three hypotheses were combined to form a failure rate distribution weighted by the hypotheses [24].

5.2. *Reasonableness of results*

Regardless of a chosen technical approach to piping reliability analysis, independent peer review processes invariably raise questions about the achieved level of realism and statistical uncertainty of quantitative results. How well do the results compare with the applicable service experience data? Has the plant-to-plant variability in piping system layout and degradation mitigation practice been properly accounted for? A particularly challenging peer review question is the one posed when no relevant service experience data is available. How should an analysis best be performed in view of zero pipe failures? Also frequently asked is whether or not a certain type of technical approach has been formally endorsed by a regulatory agency? An assessment of the consistency of calculated pipe failure rates and rupture frequencies with operating experience improves confidence in the calculated values. There are strengths and weakness associated with each of the technical approaches to pipe failure probability calculation.

An example from NUREG-1829 involves a limited scope benchmark exercise to compare predicted weld failure rates with operating experience. This benchmark was limited to NPS 12 (DN300) BWR Reactor Recirculation welds susceptible

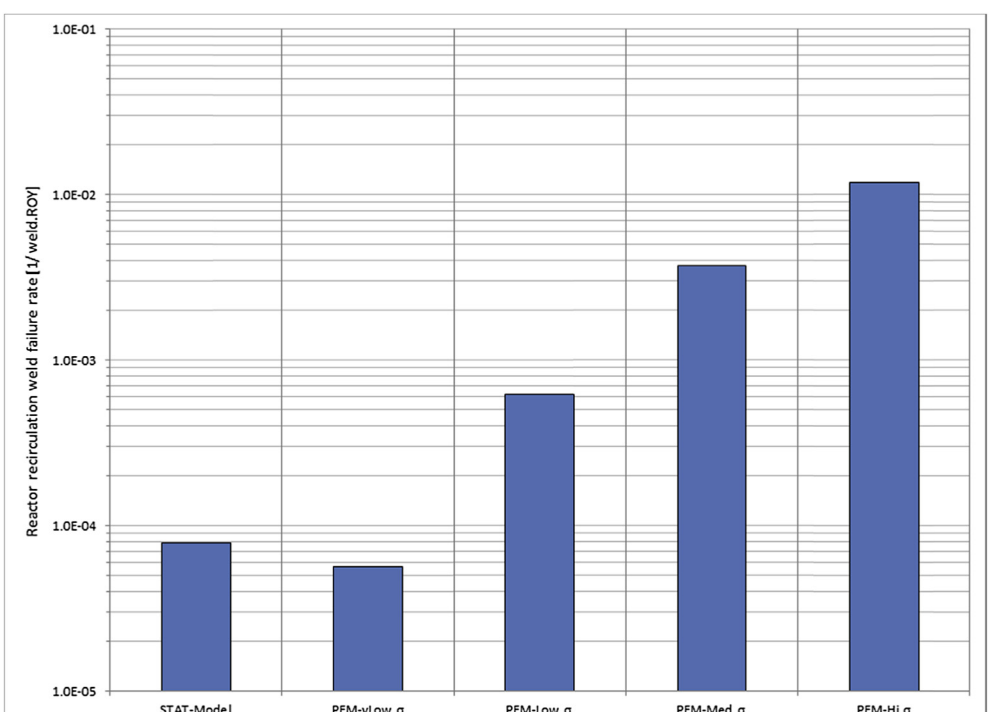

Fig. 4 – Statistical model results versus probabilistic fracture mechanics (PFM) results. Hi, high; Med, medium; vLow, very low.

to IGSCC. Probabilistic fracture mechanics calculations using the winPRAISE computer code generated predictions of weld failure rate for different assumptions about the normal operating stresses (σ_{NO}). A Bayesian reliability analysis was performed to derive weld failure rates directly from service experience data. "Failure" was defined as circumferential through-wall crack with very minor leakage (as in "perceptible" leakage). Fig. 4 summarizes the analysis cases and results [12].

5.3. *Bayesian update of pipe failure rate distribution*

Numerous published sources exist of generic pipe failure rates and rupture frequencies. Is it feasible to update a generic pipe failure rate distribution using plant-specific pipe failure data? Due to the large uncertainties and relatively low failure rates associated with piping systems, performance of plant specific Bayes' updates are not typically done. The reason for this is that there is normally insufficient plant specific evidence to justify this procedure. It has always been assumed that there would be only very small changes in pipe failure rate estimates if this type of Bayes' update were to be performed. In order to perform a technically sound Bayes' update of pipe failure rates the following questions arise:

- Is the plant specific data for failures and pipe exposure being collected and analyzed in a manner that is consistent with the treatment of generic data in the generic estimates provided in published reports?
- Is there significant plant-to-plant or site-to-site variability in the failure rate data that is reflected in the generic distributions?
- There is a question whether plant-specific data should be removed from the generic data to avoid over-counting the same evidence in two places. This is a generic issue in Bayes' updating with plant specific data but it is usually ignored under the assumption that the contribution to the generic distributions from any specific plant is small. This might not be true in the pipe failure rate case especially if the plant in question has an unusually high incidence of failure relative to the rest of the industry (Fig. 5).

- If the operating experience data points to some evidence of aging (e.g., a progressive trend upwards in the calculated average failure rate as new evidence is applied) additional work is needed to establish a good definition of the term "aging" and then to establish an appropriate statistical model. Typically only averaged failure rates are calculated over progressively longer periods. Subdividing a time period into smaller intervals might be a better approach to addressing temporal changes in calculated pipe failure rates.

While additional research is needed, it can be concluded that traditional Bayesian updating of pipe failure rates is not generally applicable. The analysis case definition needs to very specifically account for the evaluation boundary and a

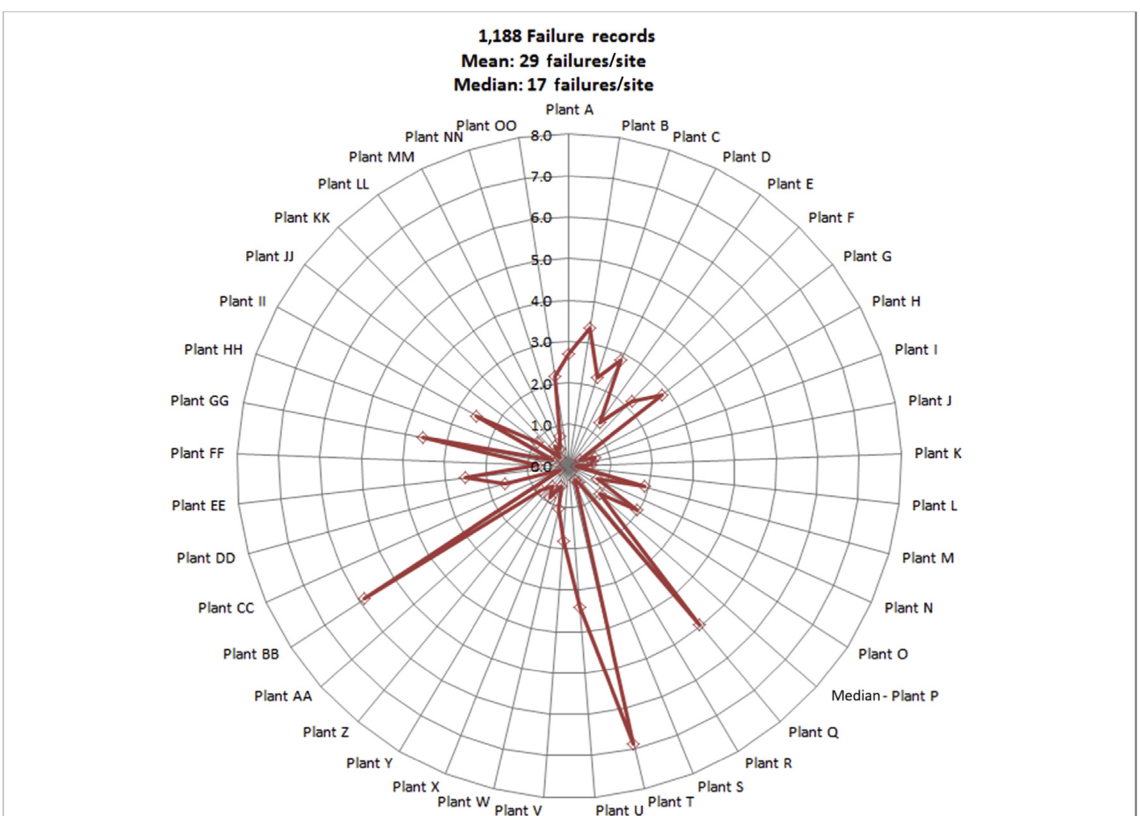

Fig. 5 – Example of pipe failure plant-to-plant variability (ratio site/median).

thorough qualitative evaluation of the failure data that is deemed applicable. Any underlying temporal shifts in the pipe failure data need to be explored further.

6. Conclusions

Insights and lessons learned from pipe failure database development and applications have been summarized into high-level guidelines intended for PSA practitioners. Assuming full access to a suitably pedigreed service experience database and strong analytical tool for pipe failure rate and rupture frequency calculations, a good technical basis exists for performing analyses that meet or exceed the requirements of the ASME PSA Standard [25]. Future work includes refining the high-level guidelines and to perform benchmarking exercises for the purpose of validation and determination of scope-for-improvements.

Conflicts of interest

The author has nothing to disclose.

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